RAND

Star Wars

A Case Study of Marginal Cost Analysis and Weapon System Technology

George L. Donohue

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PREFACE

In 1984, for one of my first assignments as a research study leader at RAND, I was asked to develop a methodology to assess the marginal-cost ratio of the new Star Wars strategic defense architectures. This had been a major issue in the previous ballistic missile defense debate, and it was expected to be a major issue in the new debate. The defense systems were much more advanced, complicated, and robust compared to the 1960s architecture, however, and a new methodology was required. In addition, the technology was in a very mixed stage of development in 1984. Our study attempted to deal with these uncertainties in a highly politically charged environment.

Originally intended for publication as a chapter in a RAND book on defense planning, this report was still considered controversial enough to require considerable negotiation to secure its release for publication. It is not the intent of this study to draw conclusions on the desirability of ballistic missile defense but to present a case study of an analytical approach to an important public policy issue and describe how this analysis was received in 1985, 1986, and 1987 while many important policy decisions were being considered prior to the end of the Cold War.

The original study was done for Dr. Fred Iklé, Under Secretary of Defense for Policy, and was conducted through RAND's National Security Research Division. This report was produced by RAND using its own research funds. This case study should be of interest to students of defense policy and research and developed policy.

STAR WARS: A CASE STUDY OF MARGINAL COST ANALYSIS AND WEAPON SYSTEM TECHNOLOGY

This report presents a case study of how marginal-cost analysis can be used to influence investment decisions, not only in deciding whether to procure a major weapon system, but also how to invest R&D dollars for maximum potential leverage in the long run. The case involves the strategic defense system that the United States examined in the mid-1980s, following President Reagan's "Star Wars" speech of March 1983. The analysis presented here addressed the relative costs to the defender and the attacker in a race in which attackers added re-entry vehicles and defenders added interceptors. The initial results, based on the technology necessary for near-term deployments (by the year 2004), were very unfavorable. Subsequent analysis considered a variety of plausible technological breakthroughs and highlighted the potential value of what came to be called "brilliant pebbles," although great uncertainty remained about whether a favorable marginal cost ratio could be obtained. While the study was not a complete policy analysis, it was an important example of systems analysis: It affected policy at the time by tempering the claims of strategic defense enthusiasts and channeling R&D and architecture studies in fruitful directions.

INTRODUCTION

Marginal-cost analysis can help decisionmakers formulate both defense strategy and technical investment strategy early in the development of a major weapon system. The purpose of this report is to provide a case study that illustrates this point. The case involves a marginal-cost analysis of system architectures for the Strategic Defense Initiative (SDI). Although the application is now somewhat

dated, the nature, results, and effects of the study illustrate how critical such systems analysis is for comprehensive policy analysis in considering any weapon system for which there is a likely counter.

Background

In March 1983, President Reagan reopened the question of ballistic missile defenses in a speech announcing the Strategic Defense Initiative. It quickly became a subject for discussion and debate, with analysts attempting to find ways to assess SDI's plausibility. Many remembered that the debate over strategic defenses in the 1960s had been strongly affected by the conclusion that it would be much cheaper for the Soviets to proliferate reentry vehicles (RVs) than it would be for the United States to expand its strategic defenses. In other words, the marginal-cost ratio (MCR) was decidedly in the Soviets' favor. This hard reality played a major role in persuading the United States to accept severe constraints on antiballistic missile (ABM) deployments. The announcement of SDI reflected the belief that things had changed since the 1960s—that the United States now had or soon would have the technology to mount an affordable strategic defense that would be effective against Soviet missile attack.

Paul Nitze, a senior adviser to President Reagan on arms control and a veteran of the earlier debates and ABM treaty negotiations, soon suggested that two criteria should be satisfied before the Reagan Administration would deploy ballistic missile defenses: (1) the defenses should be cost-effective at the margin (i.e., have a favorable MCR), and (2) they should be survivable. At the request of Fred Iklé, Under Secretary of Defense for Policy, RAND undertook studies of both issues. This paper focuses on the first phase of RAND's work on the MCR issue.

Purpose and Nature of the RAND Study

The first-phase study was conducted between 1984 and 1986 by the National Defense Research Institute (NDRI), RAND's federally funded research and development center supported by the Office of the Secretary of Defense and the Joint Staff. I led the project, which included colleagues Tim Webb, Katherine Poehlman, Karl

Hoffmayer, Ken Phillips, and Jim Rosen. We concentrated on developing and evaluating a methodology to estimate the marginal cost-effectiveness of multiple-layer ground- and space-based ballistic missile systems against a Soviet threat that incorporated only limited defense countermeasures. The full study was classified, but this unclassified account should be sufficient to convey a good sense of how the study was conducted and on what information we relied.

The study postulated how several strategic defense architectures would work and simulated various Soviet attacks to determine defense effectiveness. We assumed that the Soviet response to U.S. space-based defenses would be quite simple: proliferation of offensive forces to compensate for estimated RV attrition. We also assumed minor evolutionary modifications to existing Soviet ICBM and SLBM designs. The study explicitly addressed the nature of these modifications and the threat sizing and attack scenarios. We reviewed extensive engineering data to estimate launch weights and subsystem first-unit costs. We believed that this level of detail was essential for an objective assessment.

The Political Context of the Analysis

From the time it was announced, all officially sanctioned defense studies of SDI had focused on strategy and technology, not costs.[1] Cost analysis was labeled "premature" in the early days of the program and was largely prohibited. The management philosophy was to "let a thousand flowers bloom" before cost considerations could nip any promising ideas in the bud. That approach can have merit if resources are unlimited. Ultimately, however, some criteria must be established to select areas of concentration for engineering and manufacturing developments (EMD).

In spite of the "official ban" on cost studies, we believed Under Secretary Iklé wanted the RAND study for several pragmatic policy reasons: (1) to understand the details of the arguments that would eventually have to be confronted; (2) to see how far the initial archi-

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[1]An independent 1983 summer RAND study, led by J. A. Thomson and R. D. Shaver, highlighted the importance to stability of defense-system survivability, but also looked at MCRs briefly and helped to motivate the study I am describing. The OSD also did some quiet internal study of MCRs, with mixed results.

tectures under consideration might be from satisfying the Nitze criteria; and (3) to have a basis for assessing the validity of advocates' claims and thus the actual strength of the U.S. bargaining position in international negotiations.

Major Results

In the study, then, we developed a methodology to estimate the marginal cost-effectiveness of layered strategic defenses. We applied the methodology to two types of defense architectures to identify assumptions about technical uncertainty and cost-estimating methods to which the MCR is especially sensitive. While it was not our purpose in this exploratory effort to judge conclusively the affordability or effectiveness of strategic defenses, or to choose among alternative defense architectures, the estimates that emerged helped put the SDI debate on a more empirical footing.

Many of the study's baseline assumptions were favorable to the defense. For example, we assumed that the battle management system would work within 50 seconds of ICBM launch and the space-based sensors and computers would be able to discriminate between reentry vehicle warheads and light decoys. Even with such favorable assumptions, the initial results were very unfavorable to SDI. The two architectures were found to have MCRs ranging from 1.5 to 5.8, with the higher values applying when the defense objectives were more demanding (e.g., protecting 90 percent of the target value subject to attack).

Subsequently, we considered a variety of plausible technological breakthroughs that would result in a more robust defense system design. The results indicated that space-based high-energy weapons should be eliminated and attention should be focused on reducing the weight of space-based kinetic-kill vehicles (KKVs), because we had concluded that low-weight KKVs promised the only *potentially* cost-effective space-based system. Even here, there was still great uncertainty about whether a favorable marginal-cost ratio could be achieved. The other major uncertainty was whether discrimination, reliability, and survivability objectives could be met within the necessary size and weight constraints. This system concept involving low-weight KKVs came to be known as "brilliant pebbles" and was

the primary focus of the space-based SDI concept from about 1987 to 1993.

How the Study Was Received

Interim results were briefed at the cabinet level in the Reagan Administration, and the response indicated that those results were compelling enough to "influence" (not to "determine") decisions. When the study was completed and the results were publicly presented to the Strategic Defense Initiative Organization (SDIO), they generated serious controversy and contention. Many, inside and outside SDIO, believed that RAND was anti-SDI and that the analysis was therefore biased. I believe that in fact, RAND had no position. We had simply decided to trust empirical data and the experienced designers and engineers of major defense contractors and national laboratories rather than the arguments of SDI advocates several steps removed from those who knew the technology most intimately.

One can rarely say whether any particular analysis has any specific effect on a policy decision. Policymaking in a pluralistic society is a complex process, and many workers often come to similar conclusions semi-independently. However, we can say that this was the first detailed cost analysis of SDI architectures, that it was heard at high levels with reactions indicating that the results were "new" and upsetting to some, and that many of SDIO's subsequent actions were consistent with the study's recommendations. As noted above, the program came to focus primarily on the system concept that RAND had identified as having the only potential for achieving a favorable marginal-cost ratio. Further, size and weight (the first-order surrogates for cost) became the central technological drivers of the program.

STUDY APPROACH AND METHODS

There are many ways to calculate the cost-effectiveness of a weapon system, particularly one as complex as a multilayered strategic defense system. This section describes the approach and methods that we used, that is, how we configured the defense architectures, estimated costs of defense and offense, and estimated the effectiveness

of systems by simulating defense performance against different Soviet offensives.

Configuration of Defense System Architectures

The most important basis for optimism about the United States being able to move from an offense-dominated nuclear strategy to a more defensive one was the expectation that technology would enable us to intercept ballistic missiles in their boost phase. This would require deployment of kinetic or directed-energy weapons that have very short arming and response times (typically less than a minute from booster launch) and would be able to kill targets from considerable distance.

The defense community had been studying various phases of strategic defense technology for over 20 years before the President's speech in 1983. The Army's Strategic Defense Command (formerly the Ballistic Missile Defense Systems Command) had concentrated on ground-based defense, while Air Force programs at Space Division had concentrated on satellite defense. The Defense Advanced Research Projects Agency (DARPA) had concentrated on both advanced space-based sensor and beam-weapon technology. SDI was originally an accumulation of these efforts, aimed at providing sufficient defense capability to ensure a low overall RV leakage rate.

SDI architectures were among the most ambitious and sophisticated weapon systems ever proposed. A large amount of engineering design work, subsystem testing, system integration, full-scale testing, and redesign and retesting are required to successfully field a high-technology system. Historically, it has taken at least seven to ten years to perform full-scale engineering development and to begin manufacturing a major new weapon system. Consequently, it was important to define a time frame within which weapon system development was expected to be completed.

The date on which system designs must be finalized can be deduced roughly from the desired initial operational capability (IOC) date. In judging estimates of defense cost-effectiveness, account must be taken of the time allowed for concept validation, advanced development, and full-scale engineering development. These intervals

should be consistent with those experienced in past weapon programs, even if strategic defense development were to proceed at an accelerated pace. A balance must be struck between the length of time assumed for development and the risk that the resulting technologies will be less capable or more costly than desired.

For this study, we selected an IOC date of 2004, for two reasons: First, the USAF Space-Based Laser study used 2004 as an IOC date, and the contractors based their design studies on technology extrapolations to that date. Second, intelligence estimates had been made of Soviet missile deployments out to the year 2000, so we had some basis for projecting the threat.

Assuming that ten years would be required to fully develop and begin manufacturing an SDI system, and that four years would elapse between the beginning of manufacture and IOC, only five years remained for research and exploratory development. This meant that the technologies available for incorporation into a 2004-IOC system were necessarily already being investigated in U.S. laboratories in 1984. Thus, our cost estimates had real-world antecedents. Most of the data on the technologies used in the analysis were drawn from concept-definition studies conducted over the period from 1979 to 1984.

The subsystems evaluated were assumed to be integrated into two different system architectures: As shown in Figures 1 and 2, one consisted exclusively of rocket-propelled interceptors (RPIs) and the other used both RPIs and space-based lasers (SBLs). These were selected to bracket the range of kill mechanisms being considered. The rocket-propelled kinetic-kill vehicles represented an evolutionary approach that had been under consideration for over 20 years. The space-based chemical laser represented the most mature of the revolutionary energy-beam weapons that were being investigated (i.e., neutral particle beams, X-ray lasers, etc.).

Estimating Costs of Defense and Offense

Defense cost estimates usually include research, development, test, and evaluation (RDT&E), procurement, military construction (MILCON), and operation and maintenance (O&M). Since strategic defense system specifications were still preliminary, estimates of

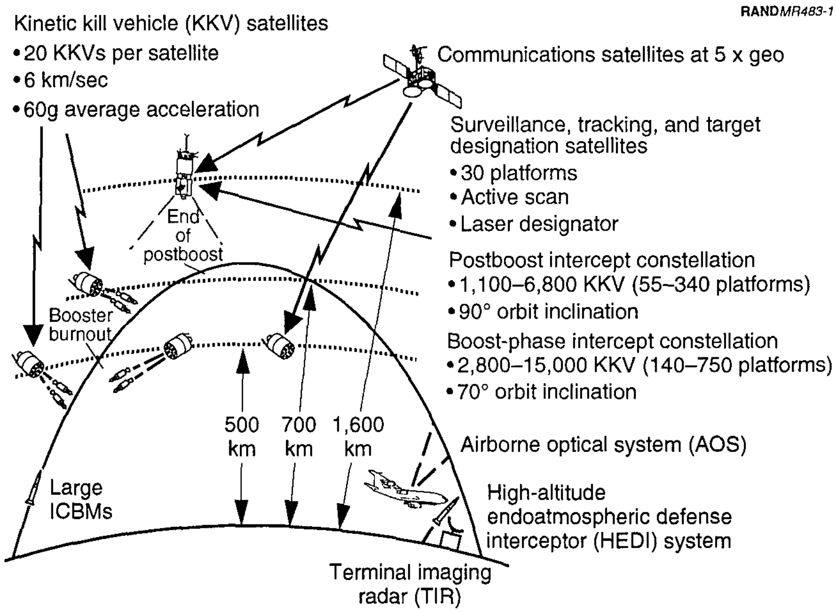

Figure 1—RPI Defense Architecture

these costs were necessarily uncertain. The most complete formulation of a cost-exchange ratio would include all types of costs, but in practice this is generally difficult to accomplish, and it was not possible under the study's circumstances.

While it is important to include as many types of cost as possible, it is equally important that total defense costs be calculated on the same basis as total offense costs. For example, if MILCON is excluded from the estimate of defense cost, it should ordinarily be excluded from estimates of offense as well. On the other hand, if space-based defense systems are designed for a 15-year life without on-orbit maintenance, then much of their O&M costs are subsumed in procurement cost. To avoid understating the cost of the opposing offensive forces, it is necessary to include their O&M costs. A similar argument can be made for treating sunk costs consistently for offense and defense.

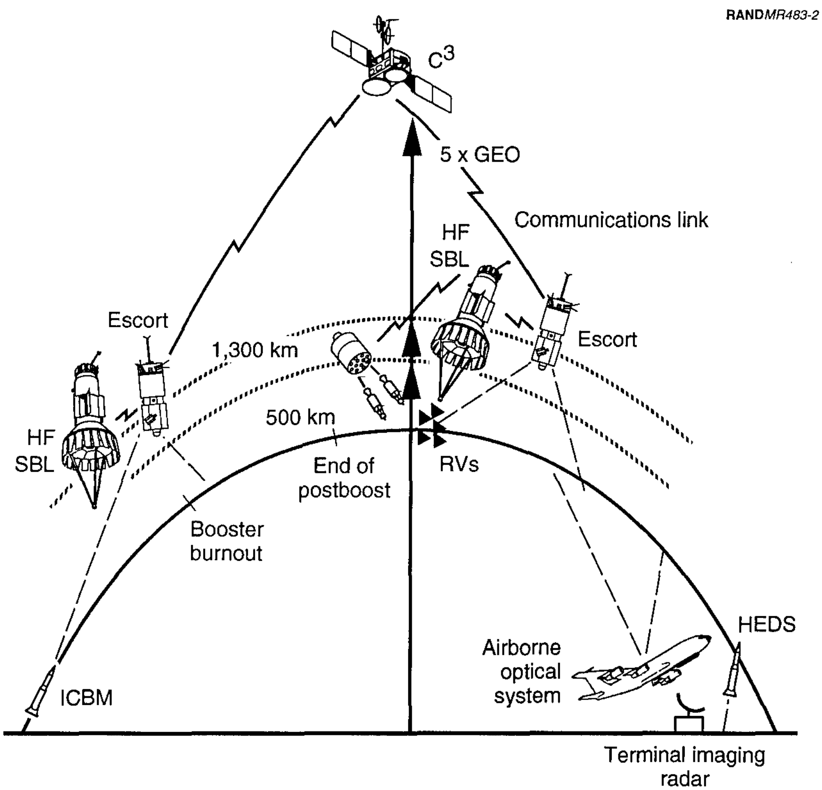

Figure 2—SBL (Boost Phase) and Chemical Rocket (Postboost, Midcourse) Architecture

Estimating the Defense Costs. Defense cost estimates rely heavily on defense contractor expectations. In general, estimates are more credible if based on detailed design information. In using this information, projections of technology maturation should be based on a combination of historical data for similar systems and forecasts by contractors. Such projections require getting information from and working directly with technical people. This study would not have been possible without the cooperation of many engineers at Martin Marietta, Lockheed, McDonnell-Douglas, Aerojet, TRW, Ball Aerospace, Rockwell International, Lawrence Livermore, Sandia National

Laboratories, Morton Thiokol, and others. By virtue of RAND's status as a federally funded research and development center, the companies granted us access to a great deal of highly proprietary information.

Defense costs can be estimated at the subsystem level (e.g., space-based laser or SBL, rocket-propelled interceptor or RPI, surveillance satellite) or at the component level (e.g., mirror, cross-track motors, cryogenic cooling components). Component-level cost estimates are best for this analysis because sensitivities of the marginal-cost ratio to current specification changes may highlight critical technologies deserving a higher R&D priority. Our study involved a good deal of component-level work, although the discussion here focuses mostly on subsystem costs.

Another important element in cost-effectiveness methodologies is the assumption about economy of scale. Learning-curve theory predicts that unit costs decrease by a constant percentage every time cumulative production doubles. For example, a 90 percent curve assumes a 10 percent decrease with each doubling. Thus, the learning curve used to calculate defense costs is a key variable in calculating the cost-exchange ratio for large-scale systems. Statements of defense cost-effectiveness based on learning-curve calculations are only as good as the assumptions that must be made in applying the learning curves: such assumptions might be fixed design, uninterrupted flow of parts and materials, and predictable production rates. If these assumptions do not hold, actual defense costs will usually be higher than predicted. In the study, learning curves were based on historical data and then varied parametrically to examine the sensitivities to advanced manufacturing technologies.

For brevity's and security's sake, and because the RPI-only design turned out to be the only potentially affordable architecture, I will describe the cost estimation only for some of its subsystems.

Choice of Launch Vehicle and Associated Costs. One of the important determinants of the cost of space-based defenses is the assumption about which launch vehicles are or will be available for subsystem deployment. Uncertainty in estimating the technical feasibility and cost of launch systems is likely to be greater for long-term options than for existing systems or their near-term derivatives. Thus the

MCRs associated with short- and long-term launch options can be viewed as reflecting different assumptions about technological risk.

We compared MCRs achieved with launch systems proposed for the post-2000 period against those achieved using launchers available in the 1990s. These cases covered a range of expectations about evolution in national heavy-lift launch capability for strategic defense purposes. Table 1 lists two of the options considered. At the time of the study, the Space Transportation System (STS), using the space shuttle, could put payload in polar, low-earth orbits (LEOs) for roughly $5300/kg (Congressional Budget Office, 1985a,b). Future launch vehicles, like the Extended BST STS (Boeing, 1984, Martin Marietta, 1984) were considered potentially able to do so for less than $2000/kg (see Figure 3).

Space-Based System On-Station Reliability. Space is an unusual environment, and special design and manufacturing techniques have been developed to ensure a high level of reliability. If these features are built in, extremely long, unattended lifetimes can be achieved (e.g., 20 years for Pioneer 6). However, older satellites are of a simple

Table 1

Future Launch Cost Estimates

Time period: Available for flight in the 1990s

Stretched Current Space Transportation System (STS)
Payload: LEO 98° from VAFB 62,000 lb or 28,000 kg
Launch cost per kg (1985 $): $3000

Shuttle-derived vehicles (SDV)
Time period: Available for flight in the 1990s and post-2000

Sidemount ULV (Martin Marietta) (1990s)
Payload: LEO 28.5° from KSC 144,700 lb or 65,635 kg
LEO 98.0° from VAFB 101,800 lb or 46,176 kg
Cost (1985 $ millions): Development: $3000
Launch cost per lb (1985 $): KSC: $493; VAFB: $1017
Launch cost per kg (1985 $): KSC: $1087; VAFB: $2242

SOURCES: *Complementary Expendable Launch Vehicle (CELV)*, Department of Defense, Report to Congress, February 1985; In-Line Unmanned Launch Vehicle System Cost Study, Final Report, Boeing, Seattle, WA, October 1984; *Sidemount Unmanned Launch Vehicle (ULV) System Cost Study,* Final Report, Martin Marietta, August 1984.

NOTES: KSC = Kennedy Space Center; VAFB = Vandenberg Air Force Base.

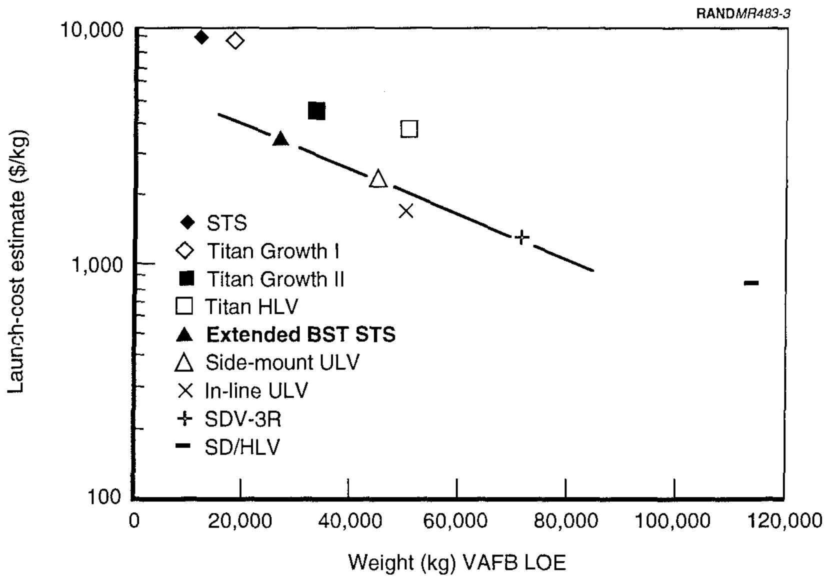

Figure 3—Future Launch Cost Estimates (1985 dollars)

design compared with the design of a surveillance, acquisition, tracking, and kill assessment (SATKA) satellite or an SBL. A statistical sampling of 78 DoD spacecraft indicated that approximately 50 percent of the satellites remain in service for as long as 5 years, and 10 percent remain in service for as long as 8 years. A goal for the on-station lifetime of the SDI systems could be 15 years. That was the figure used as the baseline assumption in this study (one of several that were defense-favorable). We also investigated the effect of requiring a 50 percent replenishment rate within this 15-year period.

SATKA Satellite Description. The SATKA satellite played a fundamental role in 1985 in the boost, postboost, and midcourse target detection, discrimination, and tracking function. In essence, this satellite had to perform the jobs of the boost surveillance and tracking system (BSTS) and the space surveillance and tracking system (SSTS). For the study, we selected the Martin Marietta SBL escort satellite to rep-

resent a conceptual design that performed both functions. The problem of multitarget tracking and decoy discrimination was not adequately addressed in this concept, so the design represented a lower bound on the size and cost of a satellite designed for the SATKA function, another defense-favorable assumption. However, the subsystem weight and cost breakdown did provide a useful point of departure for future systems analysis. The satellite was approximately 3 meters in diameter and 6 meters long.

RPIs and Carrier Satellites. A number of the contemporary studies had shown that rocket-propelled interceptors (RPIs) might be the most cost-effective weapon for a space-based ICBM defense system deployed within the next quarter century (Scheder, 1985). A major factor in these studies was the extrapolation of current technology. The cost-effectiveness of the RPI-based systems was almost totally dominated by projections of the size and weight reductions possible for vehicles that could achieve exoatmospheric velocities between 3 km/sec and 10 km/sec.

Each organization used different case and nozzle materials, expansion ratios, exhaust-flame temperatures, stabilization techniques, internal pressures, solid-fuel compositions, and staging techniques. To determine whether there was agreement on what 1985–1987 technology would physically permit, we separated the designs into two categories, near-term and advanced. We drew plots of total weight versus payload weight and velocity. There was a surprisingly good fit of all these designs to the "average design," and Figure 4 shows the results for near-term technology. There is a strong linear dependence of overall system weight on payload weight and a strong dependence on velocity (weight goes as $V^{2.2}$).[2]

The technology survey concentrated on solid-fueled (two-stage) propulsion systems, which appeared superior in cost and reliability. Figure 5 shows results for the advanced point designs, which re-

[2]Some scale distortion occurred in digitally reproducing versions of the original hand-drawn report figures. Readers should not attempt to use this and subsequent figures as precise sources of data.

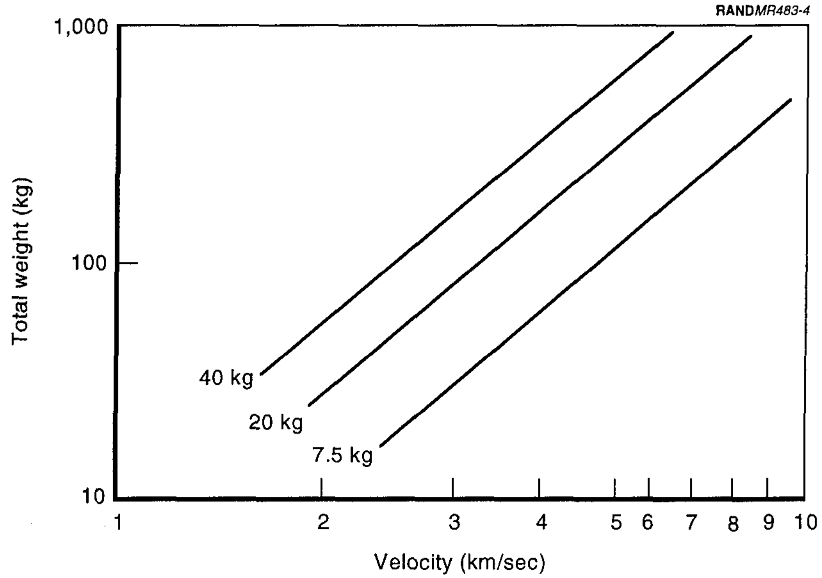

Figure 4—KKV Weight Versus Velocity (Constant Payload): 1985–1987 Technology

flected a belief by the manufacturers that a weight reduction of approximately 37 percent could be obtained with advanced rocket technology by 1995. None of them wanted to comment on designing and manufacturing a divert velocity system for total payloads weighing less than five kilograms.[3]

RPI Weight and Cost Estimates. The cost of manufacturing a space-based RPI was difficult to estimate. Some guidance could be obtained from the few systems that had been produced or had production cost estimates generated. The main sources of data used were ALTAIR III cost estimates provided by Morton Thiokol and the

[3]These estimates preceded the Lawrence Livermore estimates made by Lowell Woods that led to the "brilliant pebbles" concept—a concept that this MCR analysis indicated was attractive.

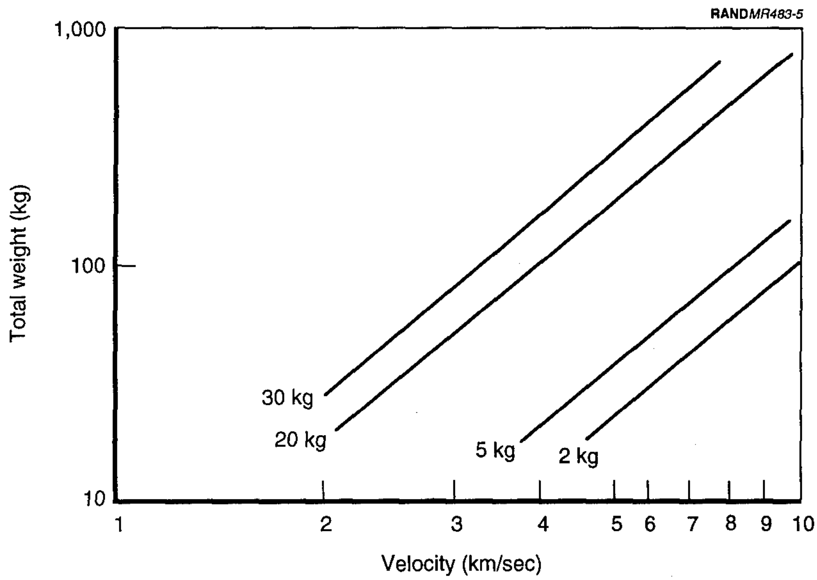

Figure 5—KKV Weight Versus Velocity (Constant Payload): 1990–1995 Technology

Martin Marietta/Ball Aerospace RPI design study conducted for the Air Force SBL study.

Since large numbers of these systems were expected to be manufactured, the designs had to be amenable to mass-production techniques (i.e., the Advanced ALTAIR rocket motor (STAR 20A) uses a glass fiber/epoxy pressure vessel, rather than the machined titanium pressure vessel of the STAR 24). The ALTAIR III was one of the few solid-fuel space-based rockets ever designed for large-scale production (e.g., the Advanced ALTAIR was used as the final stage of the F-15 ASAT/MHV weapon, and the ALTAIR III was used as the SCOUT fourth stage).

The first-unit cost of the Advanced ALTAIR motor was estimated to be $171,000. The rocket weighs 315 kg, uses an HTPB/AP fuel mixture, and has a specific impulse of 293 sec, a fuel mass-fraction of 0.91, and a nozzle expansion ratio of 44:1. This equates to about $540/kg (1985 dollars). The rocket motor accounts for most of the

RPI weight but contributes little to the overall production cost. The homing sensor optics and electronics were considered to dominate the cost of any future self-guiding space-based RPI.

Martin Marietta/Ball Aerospace estimated the first-unit cost of their RPI system to be $4.5 million (341 kg total weight). The rocket motor for their design was very similar to the ALTAIR III. By subtracting the rocket motor cost from the total cost, we inferred that the front-end first-unit cost would be about $102,000/kg (1985 dollars). This was in line with other space-based electronic cost estimates (RAND research performed in 1984 by Kenneth Horn and Elwyn Harris, and the COMSAT/SATKA estimates).

Using these cost guides and Figures 4 and 5, a first-unit cost estimate could be made for a baseline system at two different primary velocity and cross-track velocity values. We assumed that (1) RPIs used only for self-defense or midcourse would use 4 km/sec primary and 200 m/sec cross-track velocity and (2) RPIs used for boost, postboost, and midcourse would use a 6 km/sec primary and 300 m/sec cross-track velocity.

Figure 6 (see points labeled RPI/KKV) shows how these two average cost estimates compared with average cost data obtained for the Patriot, Pershing 1A, Atlas, Polaris, Poseidon, Minuteman I, II, and III, MX, Titan I and II, Spartan, and Sprint missile systems. At the top left of Figure 6 is a point corresponding to a frequently stated goal of the SDI program, which was to develop a 2-kg RPI warhead (i.e., 30-kg total RPI weight), which would later be labeled a "brilliant pebble." If such a vehicle were developed, we estimated its first-unit cost from Figure 6 to be $16,000/kg.

RPI Carrier Satellite Weight and Cost Estimates. Because of the requirement that RPIs must be of minimum size, weight, and cost, the contemporary assumption was that they could not provide all communication, thermal control, station-keeping, and power functions for themselves. They were assumed to be carried into orbit and maintained on station in a "carrier" satellite (see Figure 7; the top part shows the carrier satellite with 12 RPIs, each one of which was as

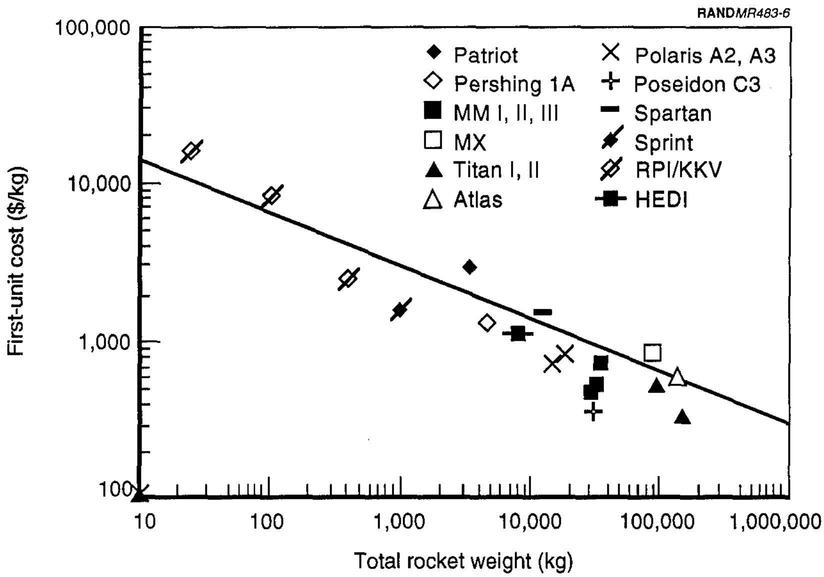

Figure 6—Estimated Guided-Rocket First-Unit Cost Estimates (1985 dollars)

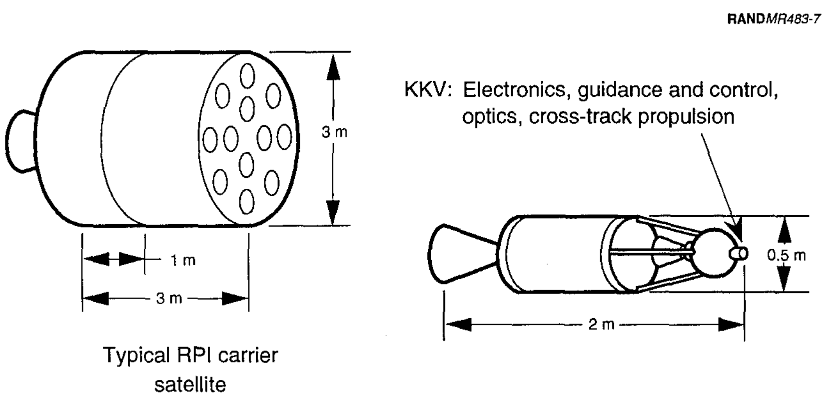

Figure 7—Typical Carrier Satellite and RPI

shown in the bottom). Figure 8 shows the Aerospace Corporation estimate of the weight sizing relationship that was considered appropriate for this carrier satellite at the time (based on research performed in 1985 by Aerospace Corporation). Structure overhead is the weight—measured as a multiple of the weight of the structure sufficient to bear the burden of the RPIs plus communications, power, thermal-control equipment, etc.[4]

Survivability considerations would indicate that maximum dispersal (i.e., the minimum number of RPIs per satellite) is the optimum deployment strategy, but for small numbers the structural weight becomes a large fraction of the total—thereby raising costs substantially. Figure 8 shows that the structural weight overhead approaches an asymptote of about 1.5 as the number of RPIs per carrier satellite increases.

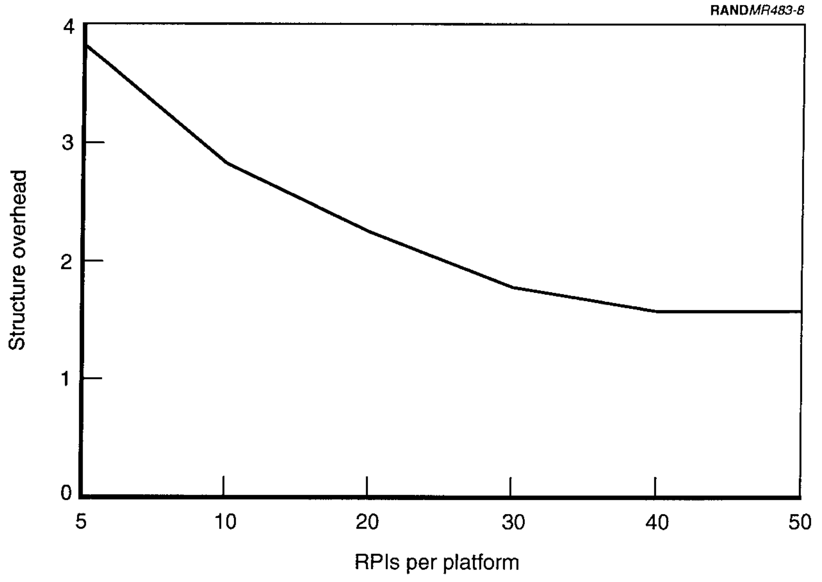

Figure 8—RPI Platform Weight Versus Number of RPIs per Platform

[4]Structure overhead is defined by S = {total loaded satellite weight} / {(fuel mass fraction)(fixed electronics weight + sum of weight of RPIs)}.

These considerations led us to select about 20 RPIs per satellite for the 6-km/sec RPI and 60 per satellite for the 4-km/sec RPI. Figure 9 shows realized and projected cost estimates for a number of space-based systems as a function of in-orbit dry weight (weight without fuel, which does not contribute significantly to cost). The STS cargo bay limitations tend to restrict the carrier satellite's weight to between 4000 and 10,000 kg (excluding RPI weight). This would indicate (see the range between the two points for RPI/KKV carrier satellites) that the carrier satellite vehicle alone should cost about \$35,000/kg (first-unit cost, 1985 dollars).[5] Size, weight, and cost estimates were made for each element shown in Figure 10, using a similar level of detail in the analysis.

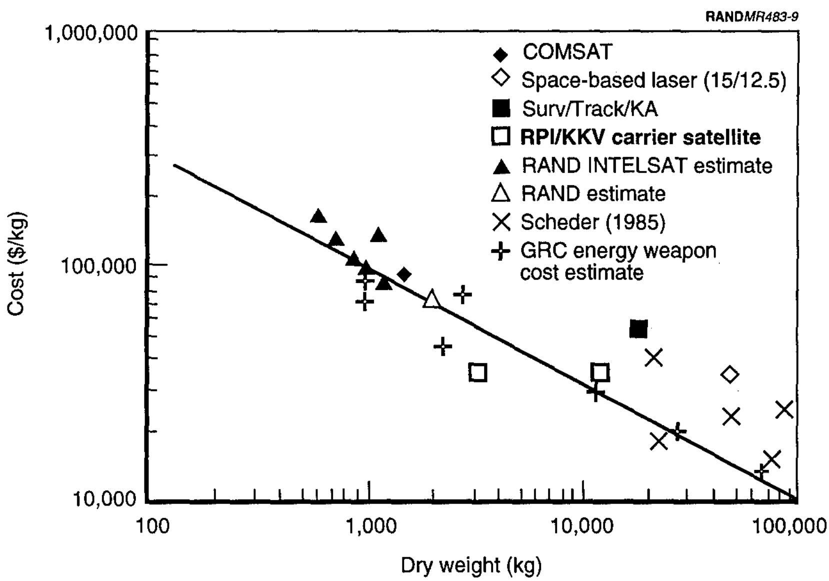

Figure 9—Space-Based System Cost Estimates (1985 dollars)

[5]The realization that the large cost of the carrier satellite tended to dominate the costs and therefore the MCR of the space-based KKV architecture ultimately led to designs without a carrier satellite, as in the "brilliant pebbles" concept.

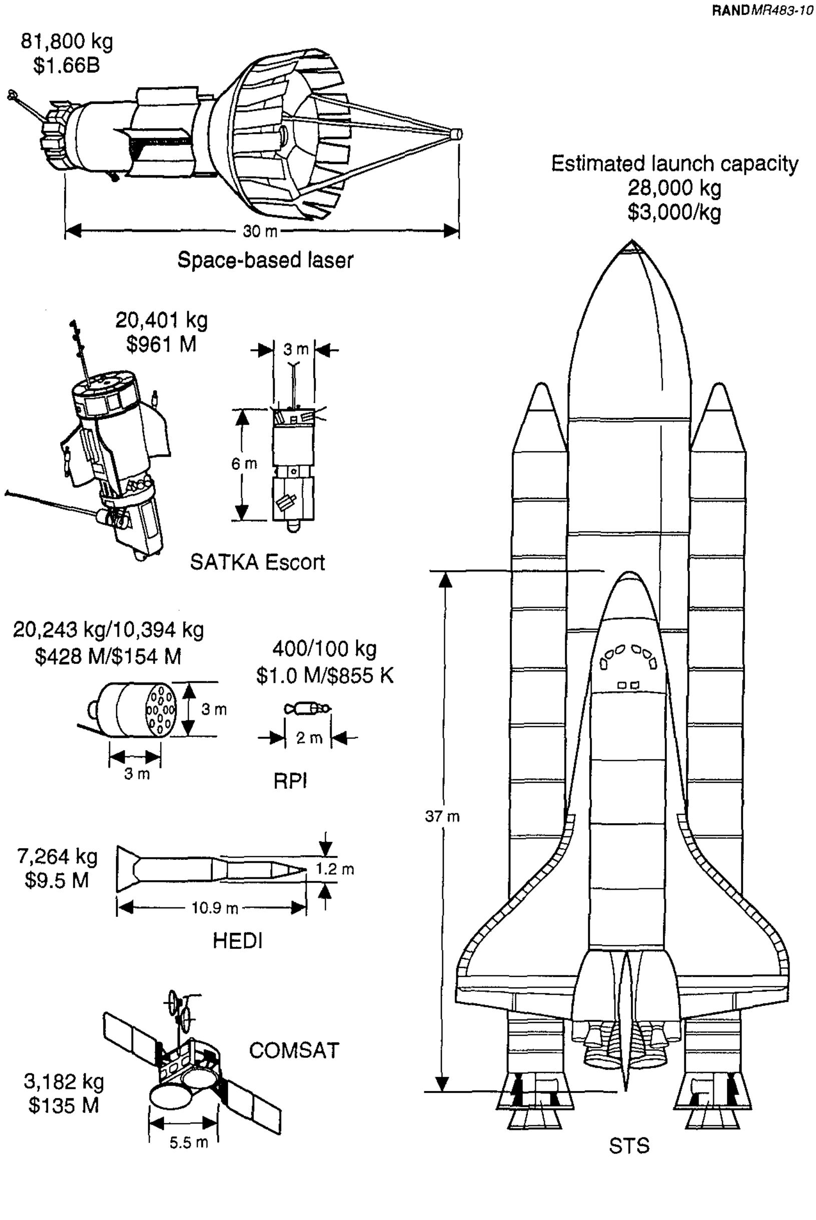

Figure 10—Summary of Launch Weights and First-Unit Costs of Major Subsystems Evaluated in This Study

Estimating Offense Costs. Assumptions about Soviet force structure are also critical in the cost-effectiveness calculation. The Soviets might have responded to deployment of U.S. strategic defenses in various ways, including:

- Retargeting and/or proliferating offensive forces (boosters and/or RVs).
- Changing the structure of offensive forces (proportion in bombers and cruise missiles, basing areas, mobile versus fixed, etc.).
- Making qualitative improvements in present offensive forces (including replacement modernization), e.g., fast-burn boosters, booster hardening and booster roll against directed-energy weapons, increased booster maneuverability, maneuverable reentry vehicles (MaRVs), and/or decoys.
- Deploying ground- and/or space-based strategic defenses.
- Deploying defense-suppression forces.
- Changing launch tactics (clustering mobiles, time coordination of spatially distributed attacks).

Soviet actions were constrained by national economic and technological means, as well as by their expectations regarding U.S. capabilities and intentions. It was difficult to quantify the opportunity costs that would be incurred by the Soviet Union in shifting economic resources in response to the deployment of robust U.S. strategic defenses from, for example, procurement of strategic offensive forces to procurement of defense suppression forces. Consequently, the study concentrated on a methodology for quantitative MCR estimates in which only the proliferation of Soviet offensive forces was considered. We assumed this would be the "easiest" response, but not necessarily the most effective one.

The MCR includes explicit assumptions about the cost of the offensive threat. Since the cost of U.S. defense is expressed in dollars, dollar estimates are needed for the cost of Soviet missiles. We considered two approaches: (1) estimating dollar costs for Soviet missiles on the basis of the dollar-equivalent costs of the most modern U.S. ICBM (the MX) translated to Soviet weapon systems; and (2) re-

lating dollars per kilogram and total missile weight for U.S. missile systems, then applying this relationship to Soviet missiles, using their total weight.

For the first approach, the method of assigning dollars to Soviet missiles was to use an MX $/kg analog for all Soviet missile types. This approach and method may, however, ignore important differences between the U.S. and Soviet economies. It may overstate Soviet costs if inefficiencies in the U.S. procurement process would have caused the U.S. cost of buying missiles to be higher than "true" Soviet costs, or vice versa.

At the time, many SDI advocates were using the MX (Peacekeeper) costs as a surrogate for Soviet ICBM costs. The problem with this approach was that the MX program was, by far, the most expensive of any U.S. missile program. Because of political constraints, only 100 MX missiles were ever produced, and the entire R&D costs were amortized over that number. The negligible economies of scale led to inordinately high cost estimates for Soviet missiles—which faced no political constraints and were usually procured in large numbers. Consequently, using the MX $/kg analog would result in an unreasonably defense-favorable assumption about relative missile costs.

These considerations led us to take the second approach and estimate the dollar cost of Soviet missiles by reference to estimated first-unit costs of all other existing and proposed U.S. guided-missile weapon systems (as shown in Figure 6). The first-unit costs were estimated assuming a 90 percent learning curve and known production totals. Soviet missile flyaway costs were then calculated by assuming their first-unit costs per kilogram.

Operation and support costs for Soviet missiles were based on estimated annual O&S for Minuteman of $135,000 per missile. These costs were ascribed to Soviet missiles for 15 years, the same interval as the baseline on-orbit lifetime of the space-based systems of the U.S. strategic defense architectures. Lack of information led us to exclude MILCON for both offense and defense (these costs were estimated during Phase II and were found to be negligible). Research and development costs were excluded for both offense and defense, because we could not find a reasonable basis on which to estimate

them, and one might argue that they should not affect the MCR estimate.

The Soviet Union had already procured some fraction of the inventory value of strategic offensive forces it would have available early in the next century. This portion of value (the sunk costs) was not included in the Soviet attack cost used to calculate the MCR; only those expenditures in anticipation of or in response to defense deployments were counted. A similar argument applies for defenses, but little if any of the defense capability to be available for the year 2000 would already be deployed. The Soviet Union had already paid much of the cost to move to the margin, while the counterpart costs for the United States remained to be incurred.

The Soviet force posture used in this analysis assumed several evolutionary modifications to the SS-18, SS-19, and SS-N-20 reentry systems by the time of defense IOC. Each modification was assumed to cost the Soviets 15 to 25 percent of the original flyaway cost per missile. This was an average of the proportion of total program cost made up by guidance and control of existing U.S. ICBMs and SLBMs. In this way, the Soviets were charged for modernization of existing missiles after 1985. Sunk costs were the estimated dollar flyaway costs of missiles in the Soviet inventory as of 1985; costs incurred in modernization were not sunk costs for purposes of this analysis.

The Effectiveness of Defenses Under Different Threats

Estimating the effectiveness of defenses required that we (1) define the attacks to be met by the defense and (2) simulate defense performance against these attacks.

Threat Definition. Since marginal cost-effectiveness of defenses varies with the defense objective, it is important to consider a range of attack scenarios and the performance of the defense against those attacks. The scenarios used in this study are shown in Table 2.

Many interesting attack scenarios were not represented in this analysis—for example, a limited Soviet attack on the U.S. politico-military leadership, in which the Soviets wish to achieve high damage expectancy with high confidence. This high confidence becomes sub-

stantially more difficult to achieve once strategic defenses are deployed.

The five scenarios of Table 2 were chosen to be representative in size and geographical dispersion of attacks the Soviet Union might launch. No judgment is implied as to which of these attacks is most plausible or likely. In the smallest attack (scenario 1), the Soviets launch all of their cold-launch ICBMs (SS-18s) at U.S. strategic offensive forces and associated command, control, and communications (C^3). This attack choice leaves the option to reload SS-18 silos. In the next-larger attack (scenario 2), all SLBMs and hot-launched ICBMs are launched; mobile missiles are withheld. The attack of 8000+ RVs involved a larger fraction of Soviet ICBMs to cover a wider range of targets, including garrison areas for U.S. forces. The attack of 12,000+ RVs (scenario 3) was a comprehensive countermilitary attack, covering all strategic offensive forces (SOF), C^3, and conventional force targets. The two largest attacks are the most stressing to the defense and involve strikes at war-supporting industry (WSI) as well as military targets. The 18,000+ RV attack (scenario 4) reflects our nominal estimated MIRVing for Soviet forces by the year 2000. The 23,000+ attack (scenario 5) was a higher estimate, representative of one option the Soviets might have taken in a heavy-MIRVing proliferation response to strategic defense deployments. The Soviet airbreathing threat was not included in this analysis.

Table 2

Scenarios Used in Simulations

Scenario		Approximate Number of Reentry Vehicles
1.	Cold-launch ICBMs vs. SOF/C^3	4000
2.	Partial launch of all ICBMs vs. SOF/C^3	8000+
3.	All ICBMs vs. OMT/SOF/C^3	12,000+
4.	All missiles vs. WSI/OMT/SOF/C^3 with increased MRVs	18,000+
5.	All missiles vs. WSI/OMT/SOF/C^3	23,000+

Figures 11 and 12 depict the Soviet attack trajectories used in this analysis. Figure 11 shows the altitude profile of the missile types included; Figure 12 shows ground tracks of 12 trajectories, along which missiles and their subcomponents fly toward targets in the United States in the two largest attacks of Table 2. The three smaller attacks use a subset of these trajectories.

Method of Estimating Defense Effectiveness. The credibility of defense cost-effectiveness estimates depends in part on the analytic technique used to determine the number of RVs leaking through several defense layers. The primary difference among these techniques is the complexity of the analytic description of offense and defense. One approach uses analytic expressions that aggregate basic characteristics of the offenses and defenses and thus might treat Soviet missile launches as evenly distributed across the Soviet landmass. The virtue of the analytic approach is that it can be calculated quickly, like a rule of thumb. Its vice is that it may obscure subtleties of the engagement that are important in determining the overall ef-

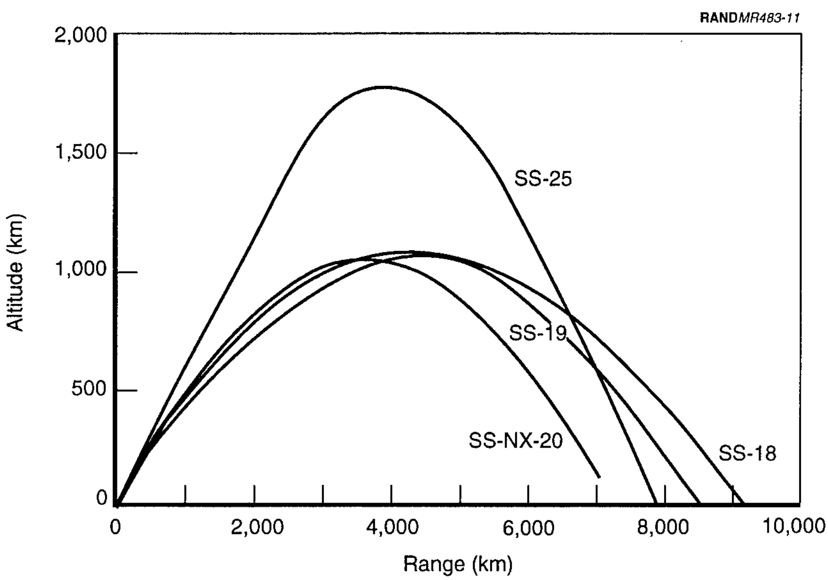

Figure 11—Missile Trajectories Used in Defense-Effectiveness Calculations

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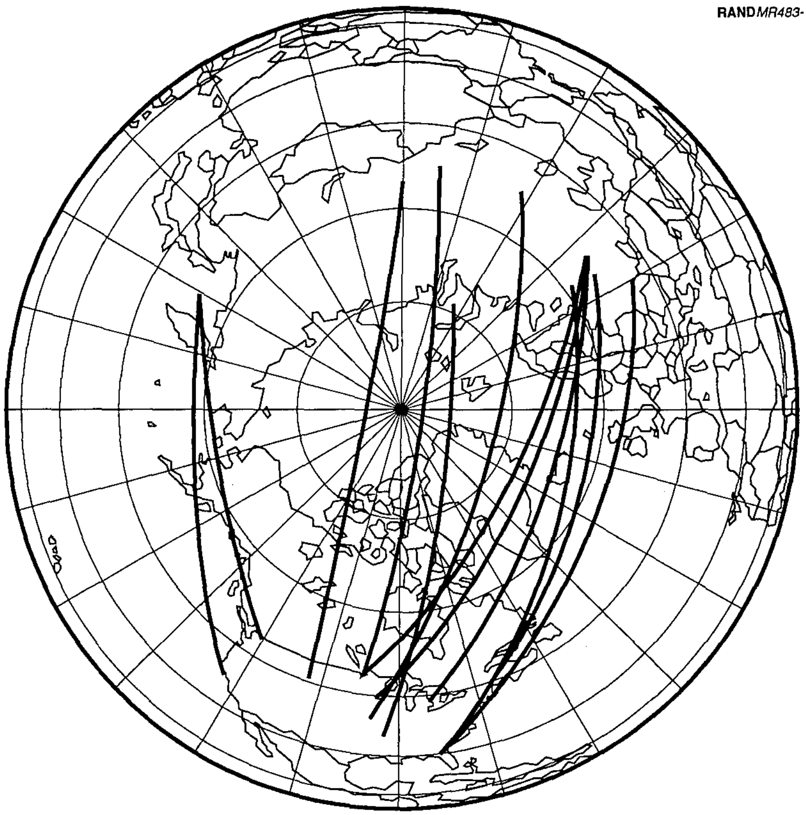

Figure 12—ICBM and SLBM Trajectories Used in Defense-Effectiveness Calculations

fectiveness of the defense. Many studies of the time were using simple analytical representations of an aggregated system, especially in the unclassified open debates (e.g., between Gregory Canavan of the Los Alamos National Laboratory and the American Physical Society).

Another approach employs simulation models that provide extensive detail about the weapon systems deployed by both the offense and the defense. Such models also aggregate performance, but to a lesser degree than analytic models do. For example, the simulation ap-

proach might describe Soviet missiles as being launched from specific sites, rather than from a distributed area. Our study used a detailed simulation and optimization technique developed at RAND by colleagues Herbert Hoover and Michael Miller.

It is misleading to claim that any simulation model incorporates all the important technical factors that influence defense effectiveness. The fidelity of such models is limited by both aggregation of information and lack of information. Assumptions about the performance of defense subsystems are based on the best available engineering judgment. One example is our assumption of technical feasibility for sensors that detect, discriminate, and track targets. An alternative approach might be to explicitly model the performance of such sensors. Eventual testing of real components might also increase confidence in the accuracy of defense-effectiveness models.

There were many projects underway at the National Laboratories and FFRDCs to develop high-fidelity simulations of the effectiveness of proposed strategic defenses. These studies had produced generally coincident defense-effectiveness model results, given identical input conditions. We compared the defense effectiveness simulation models used in this study to the results of independently developed models (from research performed in 1985 by Aerospace Corporation) to ensure maximum utility of the analysis, and we found our models to be in close agreement with the best models of the time.

Simulation Methods. We used four simulation models to estimate the effectiveness of the two defense architectures that we considered (as shown in Figures 1 and 2). The models and the phases of engagement they represent are listed in Table 3.

Table 3

Phases of Engagement Modeled

Model	Architecture I RPI Only	Architecture II SBL/RPI
DLASER	—	Boost
DROCKET	Boost and postboost	Postboost
DMIDROCK	Midcourse	Midcourse
OPUS-1	Endoatmospheric	Endoatmospheric

DLASER (which was developed by Hoover and Miller at RAND) models the engagement between orbiting SBL battle stations and Soviet missiles in their boost phase. It calculates the relative positions of SBLs and boosters and calculates the possibilities for kill. The input parameters are as follows:

SBL Satellite Constellation	SBL Performance	Threat	Target Vulnerability
• No. of rings of SBL satellites • No. of SBLs per ring • Orbit altitude • Orbit inclination • Satellite phasing in adjacent rings	• Intertarget slew rate • Effective power • Brightness	• x, v for each trajectory • Launches per trajectory • RVs per launcher • Time of launch	• Damage spot size • Hardness against directed energy • Earliest shooting opportunity, and latest time of engagement, each trajectory

Each of these parameters can be varied to explore the sensitivity of results to different assumptions about the technical characteristics of the offense and defense. The dataset that characterized the target-state vectors was common in form to all of the space-based defense-system models.

Twelve different trajectories were specified, using the program COMET (Moody, 1984). Given detailed information about missile stage weights, fuel loading, etc., a launch point, and an aimpoint, COMET calculates position and velocity vectors at 10-second intervals of missile flight. These data comprise the missile kinematic information necessary for the space-based defense-system models. Each trajectory was also assigned a number of launches, which are treated as though they take place simultaneously, and a number of RVs per launcher. The space-based defense-system models thus treated the threat along each trajectory as some number of collocated boosters, postboost vehicles (PBVs), or RVs in midcourse, depending on the time since launch (see Figure 1).

In all the space-based defense modeling, it was assumed that battle management worked perfectly and that target surveillance, acquisition, tracking, designation, and kill assessment were technically fea-

sible and worked with certainty. For the SBL, this included the capabilities that enable it to lock onto a target and dwell for sufficient time to destroy it. RPIs were assumed to get frequent enough updates of target-state vector and to be sufficiently agile that they could kill targets with a probability of 0.9 or 0.8 (depending on the architecture). There was assumed to be no degradation of communications as a result of unreliability or defense suppression. These were all defense-favorable assumptions.

For each SBL or RPI satellite, the models calculated potential kills against targets along each trajectory. From this kill-possibility matrix, an optimal allocation of shots was made, maximizing the number of RVs killed: The SBL would dwell on a booster as long as necessary to kill it—the probability of kill was 1.0, assuming the laser and kill assessment were perfectly reliable. For RPIs, only one shot per target was assigned, regardless of whether excess shots were available. It might be desirable to assign multiple shots to a single target if the expected marginal return of those shots were greater than it would be if they were withheld, but this battle-management algorithm was not implemented (one instance in which our assumptions were arguably defense conservative).

Defense performance was judged by the minimum enforceable RV kills. The number of RV kills possible varies with the time the attack was launched, since the arrangement of defense satellites with respect to launch sites changes over time. Defense effectiveness was calculated for enough launch times to sample one complete cycle of constellation motion. The worst performance of the defense is the minimum kills that can be enforced. It was assumed that the Soviets would launch when they got maximum penetration of the defense: that is, the offense would fire at the time when the defense performed the *worst,* since they could track our defense satellites and make this computation. Also, the defense was preferential in that it shot first at the most valuable targets in terms of RV kills (i.e., highly MIRVed missiles). This presumed that the defense knew the type of booster that originated from any launch site. The postboost phase was modeled on the basis of average observed postboost vehicle (PBV) burn time for a given missile type, and the time intervals between RV deployments were assumed to be equal.

Both DROCKET and DMIDROCK[6] model RPI engagements. They differ in that DMIDROCK describes RPI flight using Kepler's equations of motion, while DROCKET uses a straight-line approximation to RPI flight. DROCKET is precise enough for relatively short RPI flight times, as for boost or postboost intercept, while the higher-fidelity DMIDROCK is more appropriate for long RPI flight times, as for midcourse intercept. DMIDROCK takes much longer to run, so its use was kept to a minimum. The input parameters for these models are identical, as shown below:

RPI Satellite Constellation	RPI Performance	Threat	Target Vulnerability
• No. of rings of RPI satellites • No. of RPI satellites per ring • No. of RPI shots per satellite • Orbit altitude • Orbit inclination • Satellite phasing in adjacent rings	• Delta velocity during burn • Average acceleration during burn	• x, v for each target trajectory • Launches per trajectory • RVs per launcher	• Earliest shooting opportunity, and latest time engagement can finish (each of 12 trajectories)

For analysis of the RPI-only architecture, DROCKET was run twice, once for a shooting opportunity in boost and once for an opportunity in postboost, and DMIDROCK was run for midcourse intercepts. The launch time for minimum enforceable boost-phase kills was used for calculating kills in the postboost and midcourse phases. For analysis of the other architecture, DLASER, DROCKET, and DMIDROCK were run serially to determine defense performance in the boost, postboost, and midcourse phases, respectively. DLASER was run for a sample of launch times, and DROCKET and DMIDROCK were run for only that launch time corresponding to minimum enforceable boost-phase kills.

Preferential Defense Using OPUS-1. OPUS-1 is a computer program used to estimate the performance of the high endoatmospheric de-

[6]Unpublished work by R. H. Frick, RAND.

fense system (HEDS) in a strategy designed to preferentially defend the target base.

Principle of OPUS-1 Model Operation. OPUS-1 was designed to evaluate the effectiveness of defending a fixed set of targets with preferential strategies (Hogg, 1981) and was modified for use at RAND. The model operates according to the following ground rules:

- The defense protects its targets with a fixed quantity of interceptors.
- The offense attacks the target database using a fixed quantity of RVs.
- Each RV has a probability, *P(k)*, of destroying the target at which it was aimed.
- Each defending interceptor has a probability, *P(j)*, of intercepting an RV to which it was committed.

For this study, both the offense and the defense knew the location of all targets, as well as the inventory and performance of weapons available to the other side. Neither side knew the opponent's allocation of available weapons to the target base.

The specific allocation of offensive and defensive weapons defines a pair of preferential strategies, and the theory of two-person zero-sum games defines the mathematical framework according to which a side chooses its allocation. Both sides must have the same utility function in order to derive a game solution to the target allocation problem. OPUS-1 specifies that function as the expected value of the number of targets that survive the attack. The model calculates the optimal allocation of weapons as the saddle point that defines the strategies for the two sides. If the offense chooses a strategy other than the calculated optimal strategy, then the defense can increase the expected value of the surviving targets. Conversely, if the defense tries to operate in a way other than according to its optimal strategy, the offense can decrease the expected value of the surviving targets.

The Specific Variables We Used. We chose a total of four categories to represent the different target types among which the offense and defense could allocate weapons. A total of 3500 targets were included. The targets were separated into groups to reflect differences

in both function and value. Table 4 summarizes the manner in which the target database was represented in OPUS-1. The table includes two separate leadership categories (target groups 2 and 3) and distinguishes national command authority from more localized leadership. The relative values represent weighted averages for each target group.

To study the effectiveness of multilayered defenses against different threat sizes and strategies, the target groups were combined as shown on the right-hand side of the table. For the scenario representing attacks against strategic offensive forces (SOF) only, we described only target groups 1 and 2 to the OPUS-1 model. We added target group 3 for the scenario describing attacks against SOF and other military targets (OMT). Finally, we included group 4 to study attacks against all targets including war-supporting industry (WSI sites).

Table 4

Target Categories in OPUS-1

				Targets Selected for Different Scenarios		
Target Group	Target Description	Number of Aimpoints	Average Target Value	SOF	SOF + OMT	SOF + OMT + WSI
1	Sub ports, MX, MM-III, MM-II, and Vandenberg	1010	3	X		
2	SAC primary and capable, C^3, leadership	386	8	X	X	
3	Time-sensitive OMT, non-time-sensitive OMT, leadership	566	11	X	X	
4	War-supporting industry, fighter-capable fields	1551	3		X	X

The two architectures (described in Figures 1 and 2) were assembled in various deployment packages. The system effectiveness of each deployment was computed using the engagement simulation models and the attack scenarios described. Drawdown curves of target value surviving were calculated for each defense deployment size by simulating defense effectiveness in the face of Soviet attacks ranging from 4000 to 24,000 RVs. The results were displayed as the percentage of target value surviving versus the size of the Soviet attack.

ESTIMATING MCR: RESULTS

Using the cost for each Soviet attack and the cost for each defense system, we could obtain the MCR for different levels of surviving target value. This section discusses these results only for the all-RPI system, because it showed the greatest potential for achieving a favorable MCR.

RPI Architecture: The Initial Estimate

The seven deployment packages evaluated for this architecture are shown in Table 5, and the cost breakdown is shown in Table 6. Boost-phase intercept cross-track propulsion requirements dictate use of the 400-kg RPI design for the baseline calculations.

The total cost for these deployments is shown in Figure 13, as a function of the number of RPIs in orbit. The largest system cost elements are the carrier satellites and the launch costs, both of which are dictated primarily by the assumed weight of the KKV terminal homing system. The baseline performance of this architecture is shown in Figure 14. This performance estimate reflects a number of baseline assumptions, most of which have been noted in the preceding description of architectures, cost, and effectiveness. This list summarizes the assumptions:

- Perfect decoy discrimination in midcourse.
- 90 percent production learning curve.
- Stretched STS launch vehicle; 28,000-kg payload to highly inclined low earth orbit for $3000/kg.

Table 5

All-RPI System Deployments

Deployment	Satellites at 500 km, 70° Inclination	Satellites at 700 km, 90° Inclination	HEDIs	AOSs	TIRs	Total RPIs	Carrier Satellites	COM-SATs	SATKA Satellites
A	143	56	1000	9	50	3980	199	9	36
B	360	143	2000	18	75	10060	503	9	36
C	552	255	3000	27	75	16140	807	9	36
D	756	342	4000	36	100	21960	1098	9	36
E	992	400	4000	36	100	27840	1392	9	36
F	1190	506	4000	36	100	33920	1696	9	36
G	1406	600	4000	36	100	40120	2006	9	36

Table 6

All-RPI System Cost Summary
(Assumes 90 Percent Learning Curve; 1985 Dollars in Billions)

Deployment	TEL/ HE DI Cost	AOS Cost	TIR Cost	RPI Cost	Carrier Cost	SATKA Cost	COMSAT Cost	Total Launches	Total Launch Cost	Total Prod. Cost	Total Cost[a]
A	13.3	1.8	3.6	1.4	44.1	23.7	2.3	237	19.9	90.1	110
B	24.0	3.2	5.1	3.0	96.8	23.7	2.3	541	45.5	157.9	203
C	33.8	4.5	5.1	4.5	144.5	23.7	2.3	845	71.0	218.3	289
D	43.2	5.7	6.5	5.8	187.6	23.7	2.3	1136	95.4	274.7	370
E	43.2	5.7	6.5	7.1	229.4	23.7	2.3	1430	120.1	317.8	438
F	43.2	5.7	6.5	8.4	271.3	23.7	2.3	1734	145.6	361.0	507
G	43.2	5.7	6.5	9.7	312.8	23.7	2.3	2044	171.7	403.7	575

[a]Does not include O&S for HEDIs, construction of launch facilities, HEDI infrastructure.

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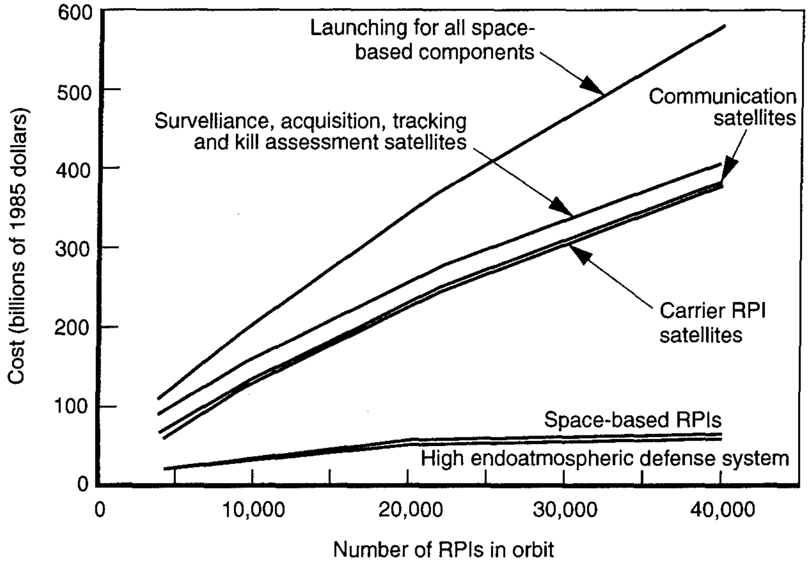


Figure 13—Defense Cost Versus Number of RPIs in Orbit, RPI-Only Architecture

- Soviet ICBM costs estimated from historical trend of U.S. guided-missile costs.
- Soviet attack costs that exclude procurement of missiles already deployed by 1985 (sunk costs) but include modification costs, costs of new missiles, and 15 years of O&M for all missiles.
- No comparable defense sunk costs.
- RPI SSPK = 0.8; RPI warhead (electro-optics and cross-track propulsion) weight = 30 kg; total RPI weight = 400 kg.
- One RPI shot in each phase of ballistic missile flight (i.e., boost, postboost, midcourse).
- Fifteen-year on-orbit life with 100 percent on-station reliability.

The drawdown curves in Figure 14 represent the RV intercepts of a given defense deployment for the entire range of attack scenarios described. The last layer of defense uses the OPUS-1 model to compute

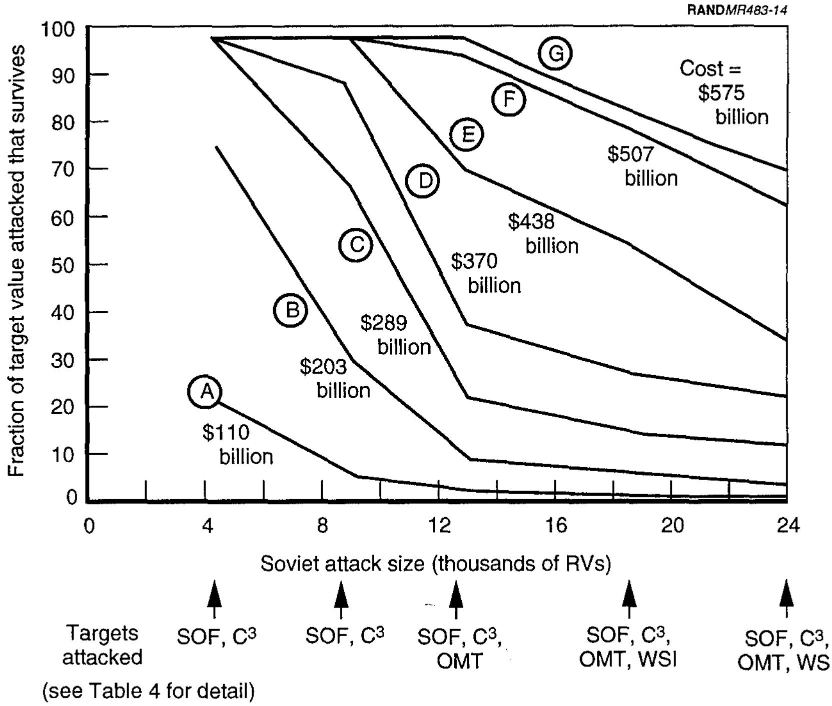


Figure 14—RPI Defense Effectiveness for Various Deployment Assumptions

the target value attacked that survives. This value is plotted for each attack scenario.

Figure 15 is replotted from Figure 14 and shows the incremental U.S. cost to defend versus the incremental Soviet cost to attack for nine different levels of target-value survival. The slope at each point along these curves is the MCR for a particular level of defense effectiveness. Within the precision of this analysis and the range of total costs considered, the MCR appears to be nearly invariant with increasing Soviet incremental cost for a given percentage of target value attacked that survives. The analytic method used did not suggest systematic differences in MCR with total cost.

Because the slope of each of these curves is nearly constant, we treated them as constant and plotted them versus percent of target

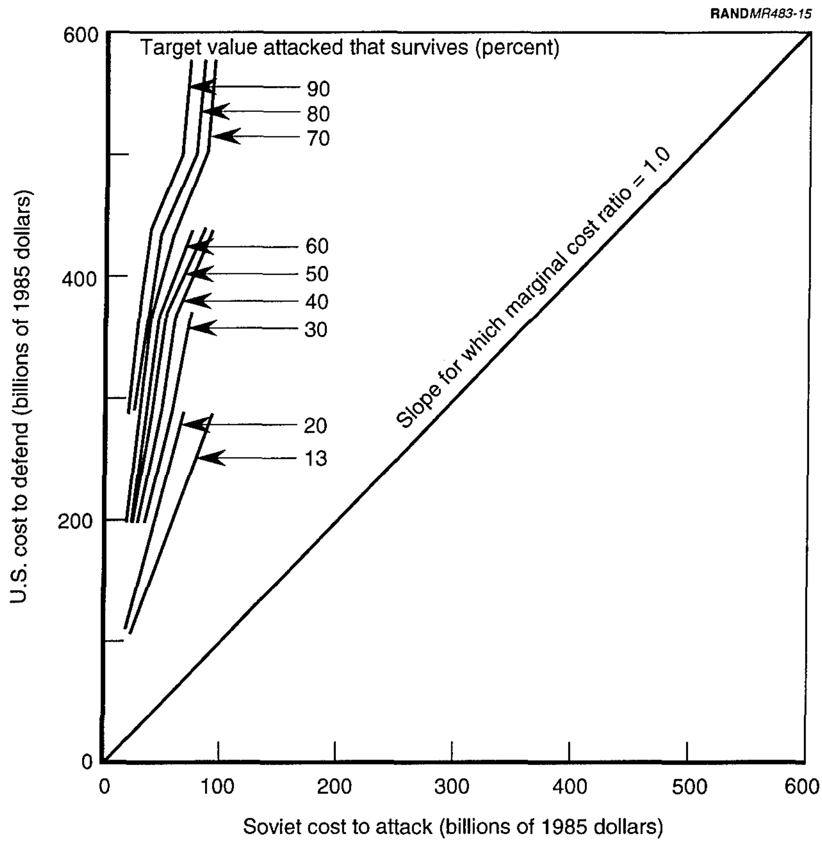


Figure 15—Cost to Defend Versus Cost to Attack for Different Levels of Target Value Surviving: RPI Architecture

value attacked that survives, as shown in Figure 16. Note that this approach would not be valid if MCR changed significantly with the scale of total costs.

The MCR associated with the RPI defense for baseline assumptions ranges from about 2.5 to 5.1. In other words, the incremental cost to defend is 150 percent greater than the incremental cost to attack for a defense objective of 15 percent target-value survival. A similar

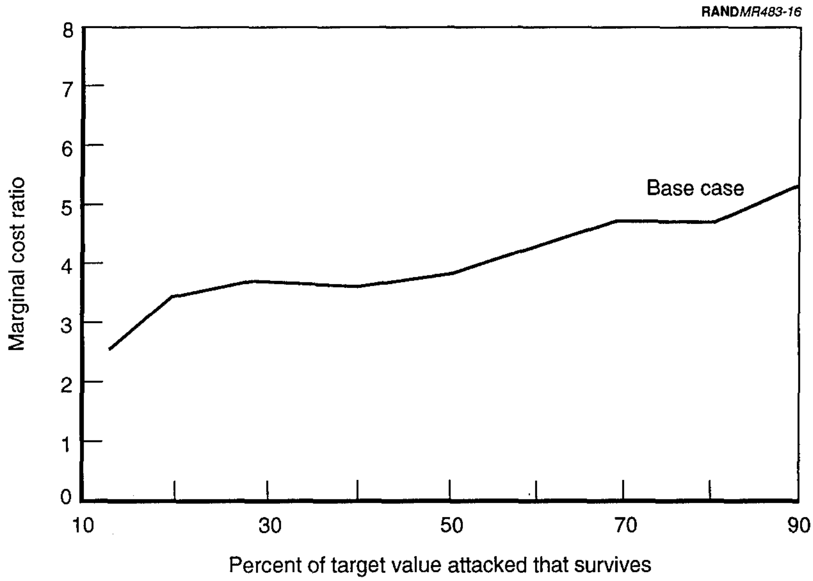


Figure 16—Baseline MCRs: RPI Architecture

analysis was performed for the space-based laser architecture, and a comparison of the results for both baseline systems is shown in Figure 17.

Reestimating the MCR for the RPI Architecture

Most of the baseline assumptions were defense favorable, which would make the estimates lower than the actual MCRs, but a few were arguably defense conservative, thereby preventing us from making simple bounding arguments to the effect that the true MCR would be worse than whatever we calculated. We therefore examined a number of excursions to see what effect different assumptions might have on the cost-effectiveness of this system.

One of the central concerns then (and now) was the ability of the space-based sensors to discriminate between real RVs and decoys in the midcourse attack phase. Our baseline assumption was perfect

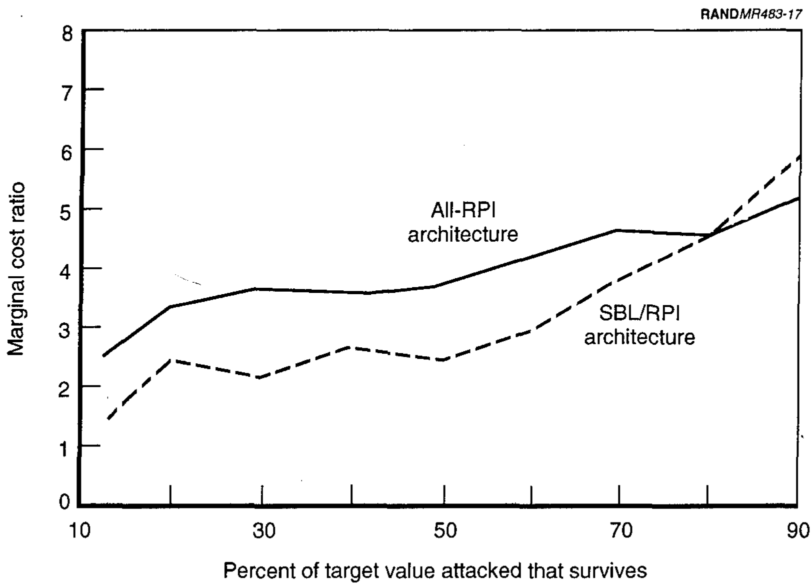


Figure 17—Comparison of MPRs for Two Architectures, Using Baseline Assumptions

midcourse detection. Figure 18 shows the increase in the MCR if the midcourse discrimination technology were not perfected.

Another assumption related to the weight of the KKV, which was seen at the time as defense conservative. We examined another major excursion to evaluate the effect of developing a very small, lightweight KKV (30 kg). The result is shown in Figure 19. This was the only system examined that produced a favorable MCR. This finding may have helped influence SDIO to put the primarily space-based "brilliant pebbles" concept through an extensive research program.

We conducted several other excursions to vary both defense-conservative and defense-favorable assumptions, the results of which are presented in Figure 20. Launch-cost reductions are often cited as a way to substantially reduce on-orbit subsystem costs. The largest

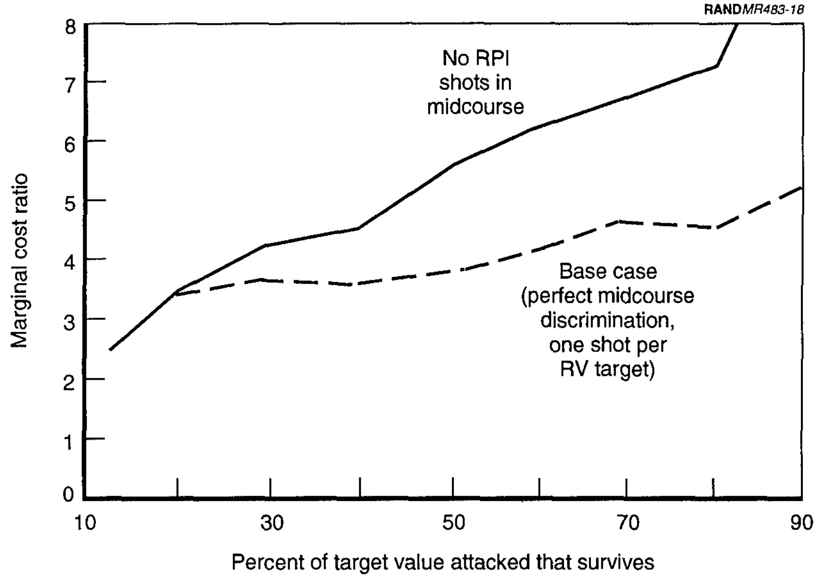


Figure 18—MCRs for Midcourse Discrimination Excursion: RPI Architecture

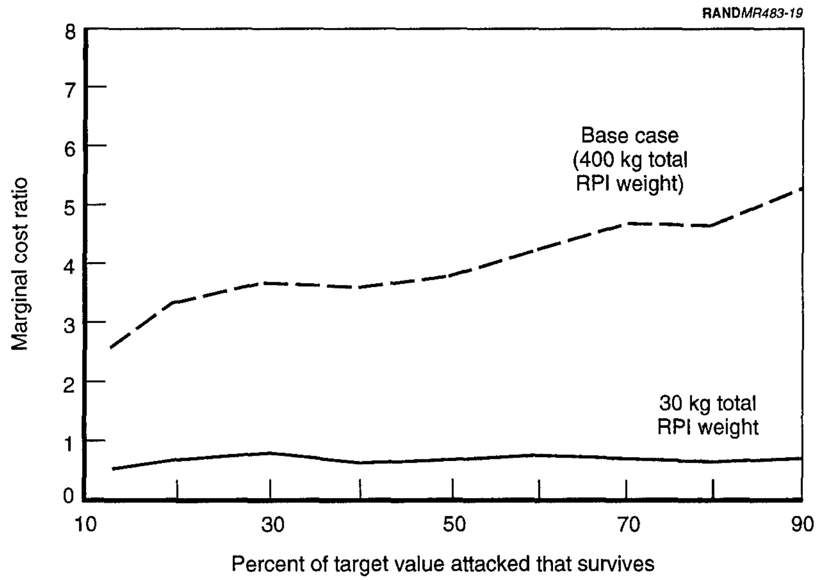


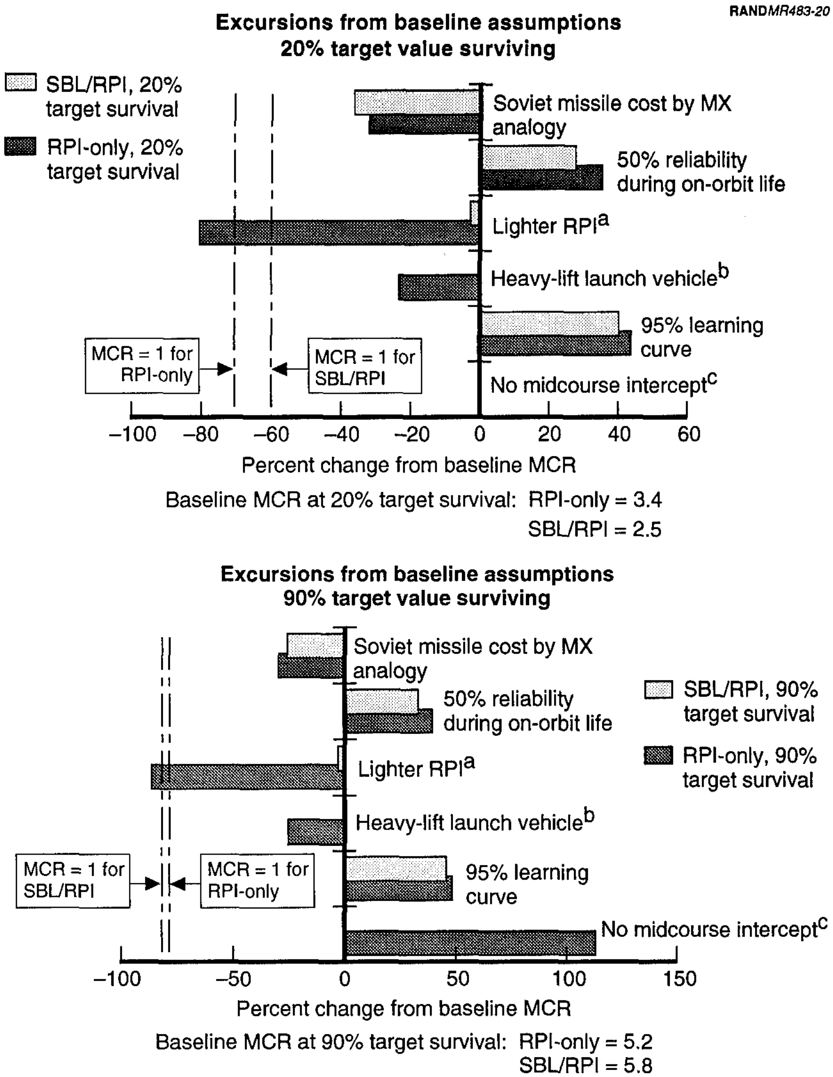
Figure 19—MCRs for Light RPI Excursion: RPI Architecture

and most cost-effective launcher estimated to be available by the year 2000 is the SD/HLV. It may be capable of lifting 113,000 kg to highly inclined low earth orbits for approximately $800/kg (Department of Defense, 1985b). This reduction in launch costs (shown in Figure 20) reduces the MCR at high levels of target-value survival by 25 percent.

We also varied the assumption that all SDI subsystems can be procured along a 90 percent learning curve. Achieving this rate would require engineering designs to be fixed for the entire run and budgets and production rates to remain stable. Design changes to increase performance, or unpredictable production rates, would undermine this assumption. The DoD has rarely experienced economies of scale consistent with a 90 percent learning curve for systems of this complexity. Even a relatively modest change (to a 95 percent learning curve) would result in roughly a 50 percent increase in MCR at high levels of target-value survival (see Figure 20). Cost escalation resulting from unpredictable production rates would result in an even less favorable MCR.

Figure 20 summarizes these sensitivities by charting the differences from baseline MCRs that result from changing assumptions about each of the six points listed above. The results of these excursions were plotted for low and high extremes of target value surviving, 20 percent and 90 percent. Vertical lines representing MCRs of 1.0 highlight the cost-effectiveness goal for each architecture. The only architecture for which this goal was achieved was the 30-kg RPI for the all-RPI defense. It can readily be seen that the SDI program should also have devoted substantial resources to improving on-orbit reliability, ensuring manufacturing economies of scale, minimizing RPI system weights (for RPI architectures), and reducing launch costs. The return in marginal cost-effectiveness of these achievements would be large. This was not to suggest that other sensitivities would not prove to be equally important. For example, we made no comprehensive effort to describe SATKA satellite performance. Indeed, by assuming that SATKA satellites would work, we undoubtedly assumed away many cost sensitivities. Nonetheless, this methodology could be used for such analyses.

Of all the parametric excursions we investigated, only the development of a 2-kg RPI warhead resulted in a defense architecture that



[a]Change from 400 kg to 30 kg total RPI weight for RPI-only defense. Change from 100 kg to 30 kg total SBL/RPI defense.

[b]SD/HLV used for all launches of SBL/RPI defense systems.

[c]Excursions not calculated for SBL/RPI defense; imperceptible change for RPI-only defense at 20% target value surviving.

Figure 20—Summary of MCR Sensitivity Analysis

satisfied the marginal cost-effectiveness goal. And even this conclusion might change if RDT&E and MILCON costs were included and amortized over the expected lifetime of the defense, or if other baseline assumptions prove to be too defense favorable.

CONCLUSIONS

This study developed a methodology for estimating the marginal cost-effectiveness of strategic defenses. We applied the methodology to two types of defense architecture in order to identify assumptions about technical uncertainty and cost-estimating methods to which the MCR is particularly sensitive. The study indicated that formidable technical problems had to be solved to make strategic defenses affordable or cost-effective at the margin. It also identified some technical breakthroughs that would have a great impact on cost-effectiveness.

Defenses whose space-based systems consist exclusively of RPIs or of a mixture of SBLs and RPIs were found to have MCRs ranging from 1.5, at 15 percent target value surviving, to 5.8, at 90 percent target value surviving. The MCR became increasingly unfavorable to the defense as the defense objectives became more demanding: for a defense objective of protecting 90 percent of the target value subject to attack, the incremental cost to defend was nearly six times the incremental cost to attack.

It was suggested that it was too early in the SDI research program in 1984 and 1985 to make any meaningful analysis of cost-effectiveness. We believed that, on the contrary, it was possible *and desirable* to begin examining cost-effectiveness issues associated with proposed architectures, so that the technology program could identify and pursue the most cost-effective options. Of the subsystems examined in detail, the greatest leverage was found to be in reducing the weight of space-based KKVs and their carrier satellites. We included an excursion in KKV weight to 2 kg (electronics, optics, structures and cross-track propulsion). This became a major goal of the program, subsequently known as the "brilliant pebbles" concept, which was the primary focus of the space-based SDI concept from about 1987 to 1994.

These outcomes illustrate the major point of the case study: the usefulness of marginal cost analysis early in the development of a major defense initiative. However, some limitations of the study and lessons learned also have instructive value.

Limitations of the Study

The reader should be mindful of several important limitations in this analysis when evaluating the results. Many points of technical feasibility were assumed (SATKA, command and control, etc.) that tend to bias the results in favor of the defense. However, some aspects of the simulations were not as favorable to the defense as they probably should have been. For example, the RPI battle-management algorithm we used could not accommodate multiple shots at targets in target-poor environments, nor could the models accommodate constellations of RPIs at different altitudes firing simultaneously. These capabilities might have substantially improved the estimated performance of the defense.

The assumptions about the technologies embodied in the defenses were not uniformly optimistic, but all were significant advances from the state of the art at the time. Some (e.g., ballistic missile command, control, and communications (BM/C^3) and discrimination) were assumed to work perfectly, a highly optimistic assumption. The costs associated with BM/C^3 were only those of the space platforms, which were expected to represent only a small portion of the total cost of this capability.

Further, we did not examine survivability of these defenses in detail, although the methodology allows for defense survivability to be subsumed in the MCR. We considered only limited Soviet responses to U.S. strategic defenses: proliferation of RVs and boosters and, in the case of a U.S. SBL/RPI defense, modest hardening of Soviet boosters to laser energy. If more sophisticated Soviet countermeasures were considered and they were to diminish the effectiveness of the defenses examined here, the MCRs would be less favorable from the U.S. point of view.

Unfortunately, it is not always possible to be consistent in these matters, and it was particularly problematic in the case of SDI. Our assumptions were necessarily a mix of best estimates and defense-

favorable concepts, with some of the best estimates perhaps too defense conservative. But our considered conclusion was that the balance was defense favorable, and probably understated the costs of the defense systems analyzed.

Another limitation was that in devising a scheme to capture a wide range of ideas about defense objectives (the percent of target value attacked that survives), we may have obscured issues that some policymakers consider important. For example, there is no explicit mention of the confidence with which the Soviets could achieve their attack objectives. We did not examine the strategic implications of these results, nor did we consider how strategic defenses might interact with U.S. offensive forces to achieve given strategic objectives. It was possible, however, to speculate that MCRs might become more favorable to the defense as technologies matured, assuming that Soviet countermeasures were limited to those examined here. Thus, policymakers could face a choice between defense systems for early deployment and defense systems for later deployment that might be more cost-effective. It was also possible to speculate that SDI might be a cost-effective component of U.S. *deterrent* strategy while not being a cost-effective means for assuring survival in the foreseeable future.

Finally, the information on defense architectures, while characteristic of the principal architectures under serious consideration, did not encompass *all* architectures that were being considered.

Lessons Learned

We focused only on cost-effectiveness at the margin. However, the study suggested the value of a more comprehensive definition of defense cost-effectiveness. The ratio of incremental cost to defend to incremental cost to attack is only one of several criteria that should be considered in judging the desirability of strategic defenses. For example, the average cost ratio would highlight the very large costs the United States would have to pay to move to the margin, i.e., the price tag for a system to counter the offensive forces the Soviets had already paid for and fielded. There are also hard-to-measure opportunity costs associated with strategic defense deployments (and SDI countermeasures). For example, the United States might accept an unfavorable MCR where strategic missiles are concerned if it in-

creased Soviet incentives to rely less on ballistic missiles and more on long-range bombers to achieve its targeting objectives. On the other hand, the United States presumably would have to forgo other defense capabilities (or other national objectives) as the price of missile defense deployments. This analysis did not evaluate these broader issues, but any attempt to examine defense cost-effectiveness in the broadest sense would have to do so.

Looking back, one of the more important lessons learned was the old lesson: Free and open debate is exceedingly important. Despite the team's best efforts to be fair and objective, our initial analysis was not perfect. And the team may even have become more anti-SDI than we realized, in part because we were reacting to what we saw as the wild claims of zealous advocates. However, because of the many technical exchanges along the way, with all the proponents of SDI generally and the technological hopes specifically, we found ourselves moving toward a set of analytic arguments and conclusions that I consider to be as objective as one is likely to find in a world filled with people and uncertainties. For example, before the study was final, we were assiduously avoiding conclusions about whether the MCR could be made reasonable. Instead, we were stating firmly supported conclusions that early deployments were likely to have poor MCRs and that the only hope for good MCRs would be a set of particular R&D breakthroughs.

Many of us were by no means anti-SDI for the long run, since we, like many others, had trouble being content with a world in which the nation's survival was not in its own hands. Strategic defenses will be considered again, and at some point in world history perhaps they will be deployed in large numbers (Shaver, 1994). But before that happens, nations will again have to consider affordability. This case study was intended to suggest what that entails.

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